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Advancing Technology for NASA Science with Small Spacecraft

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ABSTRACT

NASA's Science Mission Directorate (SMD) is strategically promoting the use of small spacecraft to advance its science portfolio. Related to this effort are an increasing number of targeted investments in instrument- and platform-based technologies, which are critical for achieving successful science missions with small spacecraft. Beginning in 2012, SMD's technology programs began to accommodate the use of CubeSats for validation of new science instruments. Since that time the Directorate has expanded the use of CubeSats and small satellites not only for validating instruments for future, conventional-class missions but also to enable a new class of focused science missions that fill an important role in democratizing scientific discovery. To enable such missions, the Directorate has recently modified the portfolios of the Agency's technology programs to accommodate this need. This paper outlines some of the processes that are used to craft the technology solicitations and discusses some of the recent selections that have been made. It is intended to help future proposers of small satellite missions to better understand the opportunities available through NASA technology solicitations.

BACKGROUND

NASA SMD is committed to enabling the scientific research community address some of the Agency's basic science questions: What causes the Sun to vary? How is the global Earth system changing, and how will it impact society? How did our solar system form and evolve? Is there life in the solar system beyond Earth, or on exoplanets of distant stars? Research programs sponsored by SMD rely upon technological innovation to build the challenging and complex missions needed to address such questions. The technology programs of SMD exist to ensure that the correct technologies are identified and investments are made to enable the science programs. Each of the directorate's four science divisions – Astrophysics, Earth Science, Heliophysics, and Planetary Science – develops a focused science program using Agency goals and guidance from the science community, especially the guidance provided by the National Academies of Science, Engineering, and Medicine, as input. Coordination of technology development within SMD and across the Agency, and ensuring the investments are sustained, are key to help ensure crosscutting technology development needs are identified and there is optimal return on investment.

The Agency's airborne and in-space flight missions, along with its scientific research and analysis programs, represent the primary customer base for SMD's technology development efforts. A recent study [1] has shown that technology readiness is especially important for flight missions because the maturity of a mission's onboard instruments and space components significantly impacts the cost and risk of the mission. SMD's approach is to mature enabling technologies years in advance of mission implementation, thereby retiring risk, reducing cost, and increasing the likelihood that new technologies will be incorporated into flight projects. Over the past decade, SMD has operated over a dozen programs to develop new technologies for next-generation science missions. Recent investments are highlighted in [2].

Acknowledging the pioneering efforts from academia that demonstrated the potential of CubeSats to perform science missions, and also responding to a more recent National Academies Study [3] that provided key insights and recommendations on how SMD should exploit small satellites, the Directorate began soliciting for small satellite technologies and science missions starting in 2012. As a result, nearly the full complement of current technology programs and science mission Announcements of Opportunity across the four research divisions have produced nearly 40 CubeSat and small satellite science and technology missions. In addition, NASA's Space Technology Mission Directorate (STMD) has played a critical role in this success. While SMD's programs have traditionally been designed to develop instrument technologies, STMD's investments provide the complementary support in developing small satellite platform capabilities, such as power systems, propulsion, communications, and thermal management.

This paper focuses on the recent changes to SMD's technology programs and the technology demonstration missions that have been proposed and that are currently under development.

HELIOPHYSICS

The Heliophysics Technology and Instrument Development for Science (HTIDS) program, which includes both science and technology elements, facilitates the use of CubeSats (along with sounding rockets, balloons, and suborbital reusable launch vehicles) as a platform for maturing new scientific instruments. Awards are typically for 2-3 years with an annual budget of ~$800K per award. Notable in the most recent 2016 and 2017 selection cycles are several CubeSat projects that will develop new capabilities for future science missions.

CURIE

The CUbesat Radio Interferometry Experiment (CURIE), shown in Figure 1, will demonstrate a two-element radio interferometer. The mission, led by PI David Sundkvist of the University of California at Berkeley, will launch as a 6U CubeSat and subsequently fractionate into two 3U CubeSats in orbit. The science goal is to use the radio interferometry to study radio burst emissions from solar flares and coronal mass ejections to better understand the space weather environment. If successful the mission could pave the way for low-cost interferometry of space-based radio observations.

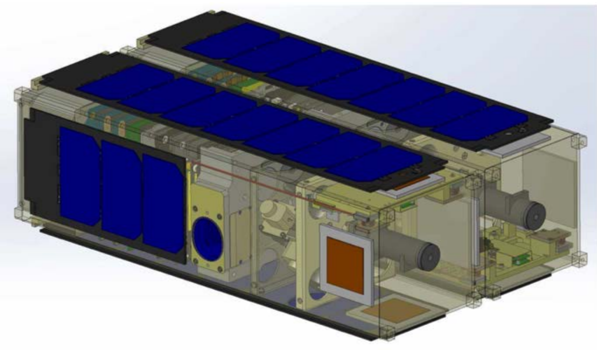

Figure 1: CURIE 6U configuration prior to separation following launch.

GTOSat

The Geosynchronous Transfer Orbit (GTO) satellite is designed to measure electron spectra and pitch angles of the seed and the energized electron populations simultaneously in the Earth's outer radiation belt. The mission will serve as a replacement spacecraft for the Van Allen Probes, which have monitored the radiation belts since 2012. In addition to its science objectives, GTOSat will accommodate a new scalable radiation-tolerant command and data handling and electrical power systems that could benefit many new small satellite missions. The mission will be the first CubeSat to operate in geostationary transfer orbit. GTOSat is led by PI Lauren Blum of the NASA Goddard Space Flight Center.

Timepix X-ray Sensor Assembly

This project will develop highly sensitive X-ray detectors to investigate flare particle acceleration. These new instruments will be developed with material that requires only passive cooling, and therefore highly useful for CubeSats. The project, led by Juan Carlos Martinez Oliveros of the University of California at Berkeley, is designed to develop capabilities for the proposed X-ray imager that would fly on a 6U CubeSat.

Time of Flight Particle Telescope

A new carbon solid state detector is being developed under this award to enable a new time of flight by energy mass spectrometer. The new diamond detector, if successful, will have a higher radiation tolerance compared to the traditional silicon and germanium detectors along with significantly faster response times. After the detector is matured and tested in a relevant laboratory environment, it would be later flight tested on a future CubeSat mission of opportunity. The project is being led by Drew Turner of the Aerospace Corporation.

EARTH SCIENCE

The Earth Science Technology Office (ESTO) is responsible for identifying and nurturing observation and information technologies to support future missions of the Earth Science Division. ESTO manages three major observation technology programs that solicit new awards on a 2-3 year selection cycle, as shown in Table 1.

Table 1: Earth Science technology programs with relevance to small satellites

Earth Science Program	Approx. Funding	Description
Instrument Incubator (IIP)	$28M / year	Nurtures the development and assessment of innovative remote-sensing concepts in ground, aircraft, or engineering model demonstrations (early to mid-stage development)
Advanced Components (ACT)	$5M / year	Enables the research, development, and demonstration of component- and subsystem-level technologies to reduce the risk, cost, size, mass, and development time of missions and infrastructure.

In-Space Validation of Earth Science Technologies (InVEST)	$5M / year	Advances the readiness of existing Earth Science related technology and reduce risks to future missions through space flight validation using CubeSats.

ESTO's current investment strategy is weighted toward the recommendations for future missions as described in the 2007 National Academy Decadal Survey [4]. The report recommended a suite of 15 missions targeted at Earth System Science, and supported by a program of smaller, low-cost missions. While the strategic Decadal missions were designed to be conventional-class, internal studies conducted during 2015-2016 suggested that up to 40% of the intended measurements from these missions could be made from smaller, ESPA-class platforms. Key instrument investment areas identified were imagers, radiometers, spectrometers, and radars; platform technologies identified included constellation management and formation flying. The study results are used to help guide new solicitation topics both in SMD and STMD programs. With the recent release of the 2018 Decadal Survey [5], the solicitations and technology investments will be reassessed to determine if additional changes in strategy are necessary.

The Instrument Incubator Program (IIP) began explicitly soliciting miniaturized science instruments for use on small satellites beginning in 2013. The most recent awards, made in 2016, resulted in 7 of 17 projects targeted at new instrument technology for CubeSats and small satellites, four of which are highlighted below. In addition, the Advanced Component Technology (ACT) program currently funds the development of instrument components and subsystems, and the majority of the 12 awards made in the most recent solicitation cycle were targeted at reducing the size, weight and power (SWaP) for the instrument systems, thereby increasing their potential for use by small satellite missions.

Solar Occultation Instrument for SmallSat Constellations

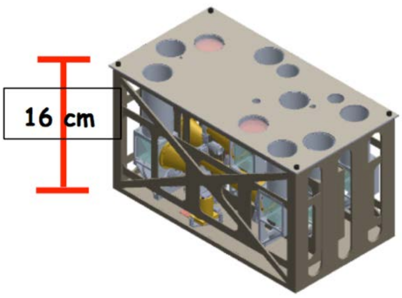

Figure 2: Conceptual design of the Gas Filter Correlation Radiometry (GFCR) Limb solar Occultation (GLO).

The Gas Filter Correlation Radiometry Limb solar Occultation (GLO) is designed to measure the vertical profile of atmospheric trace species with unprecedented accuracy for a CubeSat form factor in 23 visible near-infrared (VNIR) and short wavelength infrared (SWIR) spectral bands (see Figure 2). While the technology development is focused on the miniaturized instruments, a mission concept consisting of a constellation of 6 GLO sensors is envisioned that would enable measurements of temperature, key greenhouse gases, aerosols, and transport tracers at relatively high vertical resolution near the tropopause. The project is being led by Scott Bailey of Virginia Polytechnic Institute.

SAGE IV

The Stratospheric Aerosol and Gas Experiment (SAGE) IV Pathfinder (Figure 3) is being developed to demonstrate a new capability for measuring stratospheric ozone by using a solar occultation technique. Key to the technology development is the miniaturization of the instrument systems to fit in a 6U CubeSat, which includes a telescope design to control stray light, proper characterization of the integrated optical system, implementation of embedded control functions, and end-to-end system characterization/validation with new pointing algorithms for spacecraft operation. The work is being led by Robert Damadeo of the NASA Langley Research Center.

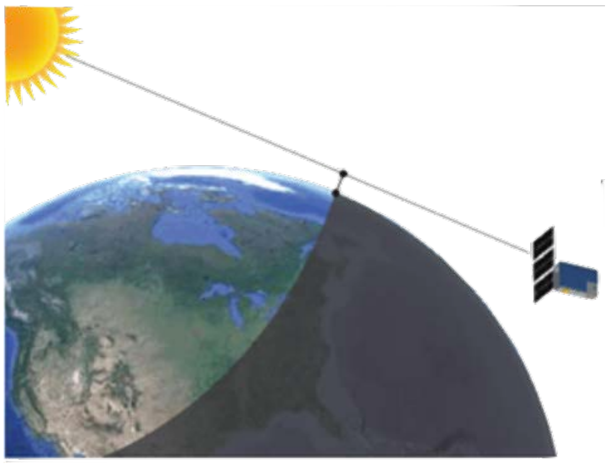

Figure 3: Solar occultation technique proposed for SAGE IV.

SWITCH

The Stratospheric Water Inventory, Tomography of Convective Hydration (SWITCH) project is developing a revolutionary approach for making high resolution measurements of atmospheric composition. The technique uses a transmitter and receiver to produce an "active microwave tomographic" capability that will measure water vapor in the upper troposphere and lower stratosphere, along with other species, to a 500m vertical resolution. The final assembly is being designed to fit in a 6U CubeSat form factor. SWITCH is being led by Principal Investigator Nathaniel Livesey of the NASA Jet Propulsion Laboratory.

Next-Generation GNSS Bistatic Radar Receiver

This project extends the capabilities of the currently-operating Cyclone Global Navigation Satellite System (CYGNSS), a constellation of small satellites launched in 2016 to measure ocean surface winds. CYGNSS measures reflectivity of omnipresent GPS satellite signals, thereby obviating the need for an expensive, active measurement. A next-generation GNSS bistatic radar receiver is being developed that will be capable of processing signals from both GPS and the European Galileo navigation satellites. As a result of the investment in hardware updates, the horizontal resolution of the measurements will be improved by a factor of three, vertical resolution by a factor of ten, and spatial coverage and revisit time improved by as much as a factor of four. Measurement quantities will be expanded as well to include soil moisture and sea level change. The project is being led by Christopher Ruf of the University of Michigan.

ESTO also manages the In-Space Validation of Earth Science Technologies (InVEST) program, one of the Directorate's first programs dedicated to validation of new Earth Science instruments in the space environment using CubeSats. Solicitations are made approximately every three years. The program made its first significant round of awards in 2012, followed by additional awards in 2015.

CubeRRT

The CubeSat Radiometer Radio Frequency Interference (RFI) Technology Validation (CubeRRT) is designed to demonstrate wideband RFI-mitigating technologies for future Earth Science missions that require microwave radiometers. As terrestrial sources of interference in this frequency range increase (see Figure 4), RFI mitigation will become critically important. The CubeRRT project employs a Field-Programmable Gate Array (FPGA)-based spectrometer with the embedded capability of executing state-of-the-art RFI mitigation algorithms such as the kurtosis and cross-frequency methods. The project is led by Joel Johnson of the Ohio State University.

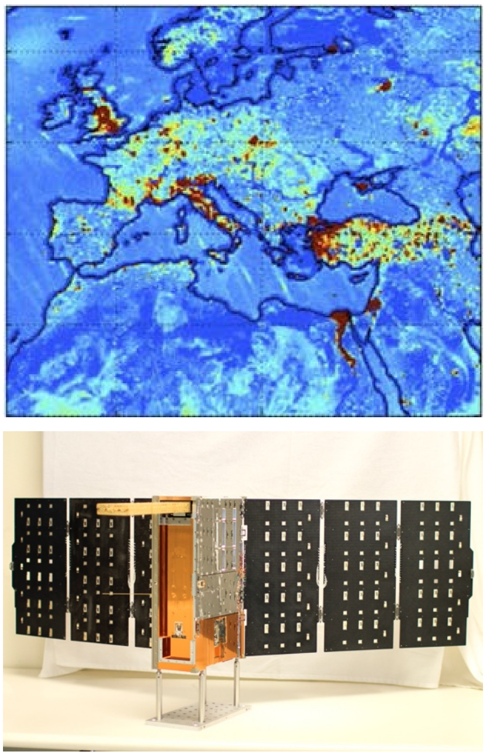

Figure 4: Top: European RFI sources at 10.7GHz (from GPM microwave imager); Bottom: 6U CubeRRT spacecraft.

CIRiS

The goal of the Compact Infrared Radiometer in Space (CIRiS) is to demonstrate the ability to perform space-based imaging of the Earth and the atmosphere in the 8-12µm thermal infrared band using a small spacecraft. The technology development focuses on reducing the radiometric uncertainty of two new components: an uncooled microbolometer detector and a carbon nanotube calibration source. If successful, the miniaturized design will greatly reduce the cost of the future missions that support studies of land use management, vegetation canopy changes, and research of the hydrologic cycle. The project is led by David Osterman of Ball Aerospace and Technologies.

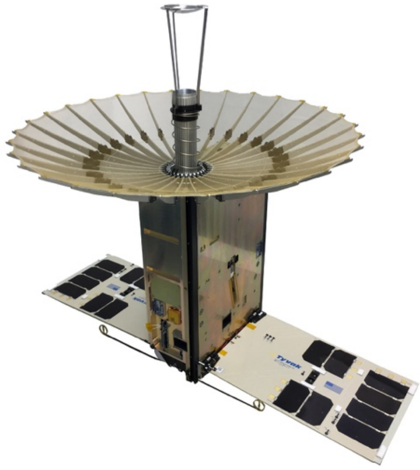

Figure 5: RainCube with fully-deployed antenna.

RainCube

Radar in a CubeSat, or RainCube, is an ambitious effort to demonstrate the operation of a Ka-band precipitation radar from a low-cost 6U CubeSat platform (see Figure 5). If successful, an operational RainCube constellation could help fill wide coverage gaps from high quality measurements such as the Global Precipitation Mission (GPM) dual-frequency precipitation radar and could significantly improve numerical weather prediction. Radars, however, are particularly challenging for small spacecraft platforms due to power and mass requirements. The RainCube project will test a novel technique, using in-space validation, to perform pulse compression while minimizing surface clutter contamination. The project is being led by Eva Peral of the NASA Jet Propulsion Laboratory.

PLANETARY SCIENCE AND ASTROPHYSICS

Science mission concepts involving small satellites for exploration of the solar system and for astrophysics research are now being developed within SMD. A 2014 study by the Keck Institute for Space Studies [6] identified a significant number of measurements that are complementary to existing Decadal Survey objectives which could be made from low cost, small satellite platforms. The study also identified a number of key instrument and platform technologies that would have to be developed in order to realize the full potential of small satellites in this area.

Following the Keck Institute report, SMD's Planetary Science Division (PSD) has made significant strides toward accommodating small satellites for its science missions.

Figure 6: MarCO CubeSats deployed from the InSight mission.

The InSight Mission to Mars, launched in May, 2018, is designed to explore the interior structure of that planet. The mission contains a technology demonstration experiment, Mars Cube One, or MarCO, consisting of two CubeSats that are the first ever to be deployed into deep space. MarCO will demonstrate the ability for a UHF radio receiver and X-band radio transmitter to provide a near real-time bent pipe relay of the InSight Entry-Descent-Landing sequence telemetry to Earth in addition to deep space navigation capabilities. If proven to be successful, the new technology could enhance future deep space communication capabilities.

PSD's Planetary Exploration Science Technology Office (PESTO) was established in 2017 to better consolidate various technology efforts operating across the Planetary Science Division. One of PESTO's first goals was to assess the potential for small satellites and CubeSats to satisfy the Division's science objectives, and subsequently to make any necessary adjustments to technology investments. The existing programs that are nurturing instrument development for a variety of observing platforms – including for small spacecraft – are depicted in Table 2. In addition to these programs that solicit with a defined cadence, other solicitations are occasionally offered to develop technologies for specific destinations, such as Europa, Titan, and Venus.

Table 2: Planetary Science technology programs with relevance to small satellites

Planetary Science Program	Approx. Funding	Description
Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO)	$4M / year	Supports the development of spacecraft-based instrument components and systems that show promise for future planetary missions. The program supports early-stage technologies.
Maturation of Instruments for Solar System Exploration (MATISSE)	$6M / year	Supports the advanced development of spacecraft-based instruments that may be proposed for future planetary missions that are at the middle stages of technology readiness.

To better engage the scientific community, PESTO recently released the "Planetary Science Deep Space SmallSat Studies" solicitation to establish design reference missions with small satellites and related technological needs. The solicitation provided funding to 19 of the 102 proposals received to produce in-depth mission design studies. In addition to providing valuable insights to small satellite science missions that could be accomplished with existing technology, the concepts were also valuable for identifying new investment needs in platform and instrument technologies. Advanced electric propulsion, high performance / retractable solar arrays, electronics and batteries operable in cold temperatures, highly-capable deep space communications, precision-pointing capabilities, new methods for entry / descent / landing, and improved thermal management were some of the key technologies identified.

Similarly, SMD's Astrophysics Division released a Request for Information (RFI) in late 2017 that sought compelling astrophysics science missions that could be realized involving small satellites, along with advanced technology concepts that would be needed for missions beyond the horizon of near-term opportunities. The solicitation generated more than 50 responses that identified the need for further technology investments in power systems, antennas, miniaturized cryocoolers, on-board processing, advanced propulsion systems for formation flying, advanced mirror coatings, and miniaturized detectors.

Both the Planetary and the Astrophysics mission concept studies will help determine new technology solicitation topics for small satellite instruments and spacecraft systems. Additional RFIs will be offered to the community in the near future.

Acknowledgments

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References

[1] U.S. Government Accountability Office. *NASA Assessments of Selected Large-Scale Projects.* GAO-12-207SP.

[2] National Aeronautics and Space Administration, 2018: *2017 Science Mission Directorate Technology Highlights,* NP-2018-04-2544-HQ.

[3] National Academies of Sciences, Engineering, and Medicine. 2016. *Achieving Science with CubeSats: Thinking Inside the Box.* Washington, DC: The National Academies Press. doi: 10.17226/23503.

[4] National Research Council (2007). *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

[5] National Academies of Sciences, Engineering, and Medicine (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space,* Washington, DC: The National Academies Press, http://www.nap.edu.

[6] Keck Institute for Space Studies, 2014. *Small Satellites: A Revolution in Space Studies.* California Institute of Technology, Pasadena, CA.